Estimating Evaporative Transpiration of Seasonally Managed Wetlands in the San Joaquin Valley

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ABSTRACT

Since the water resources of Central California are intensively used in agricultural and municipal contexts water resources available for managed wetlands are very limited and must be carefully managed. Modeling patterns of evaporation and transpiration, collectively referred to as ET, is an important step in managing irrigation regimes with the goals of limiting evapo-concentration of salts and maintaining high levels of water quality with the greatest possible water use efficiency. In agricultural systems water needs are often estimated by reference to potential ET (ETo) values, the ET of a well watered pasture plot. ETo data is readily available from weather stations reporting to the California Irrigation Management Information System from locations throughout the state. The relationship between ET and ETo in agricultural systems is well understood. This relationship is less well understood for wetlands because of the complex vegetation and moisture dynamics within these systems. A Bowen Ratio Energy Balance Station was deployed to a wetland near Los Banos to estimate ET using a Bowen Ratio Energy Balance Equation. Micro-meteorological sensors measure incoming and outgoing energy fluxes through air and soil and estimate the latent heat flux of the system, which is proportional to ET. Our estimates of ET are compared to ETo values reported to the CIMIS network. Wetland ET and ETo values do not correlate well. The dynamic nature of wetland plant communities and water resources create more complex patterns of ET than those observed at ETo plots where water resources and plant communities are intentionally held constant. Modeling of wetland ET based on ETo data will must account for seasonal changes in soil moisture and plant community composition and distribution. This research contributes to a larger project of understanding the relationships between irrigation timing, water use, water quality, and plant communities. A variety of methods, including soil salinity surveys and remote sensing estimates of plant community distributions will be integrated to model wetland moisture and plant community dynamics with the aim of improving wetland best management practices and water use efficiency while sustaining valuable wetland habitat.

INTRODUCTION

Irrigation has allowed the Central Valley of California to become one of the most productive agricultural regions in the world. The distribution of water from the California Aqueduct, the 444 mile long irrigation channel which brings water south from Northern California [1], must be managed carefully to ensure that water is used as effectively as possible. This includes management of the area's wetlands, an important habitat for migratory waterfowl. Irrigation practices must be adjusted not only to meet the water needs of the plants, but also to prevent the accumulation of salts in the soil from reaching a level which inhibits plant growth.

Inorganic salts are naturally occurring components of the soil and tend to dissolve in ground and surface water. As surface water evaporates from the surface, or is taken up by plants and transpired into the atmosphere, it leaves behind its salts, increasing the salinity of the soil and remaining water. Rainwater, which does not contain salts, will dissolve and carry away salts in the soil as it runs off the surface or leaches down through the soil. Irrigation tends to increase soil salinity because it brings surface water into an area where there is little rainwater to dilute or carry off the salts in that water. The fate of the irrigation water will largely determine its impact on soil salinity. When a large portion of the irrigation water is able to seep down into the groundwater table, or run off into another body of water, it will carry some of the salts out of the soil. If the water is lost to evaporation and transpiration, then all of its salts will remain in the soil.

In order to better understand the patterns and magnitude of evaporative transpiration over seasonal wetlands of the San Joaquin Valley a Bowen Ratio Energy Balance (BREB) Station [2] was deployed in the Gadwall unit of the Grasslands Water District near Los Banos, California. The BREB system consists of micrometerological sensors which record data including air temperature, incoming and outgoing radiation, soil energy flux, and temperature and humidity gradients above the surface. This data is used in an energy balance equation to estimate the fraction of incoming energy which is absorbed as latent heat and therefore the magnitude of evaporation and transpiration taking place.

The relationship between the ET measured on a standardized surface and the ET of a different crop or plant community is described by a crop coefficient (Kc). These are calculated by simultaneously measuring ET over the standard surface and the crop of interest when both are grown in similar climatic conditions [4]. A larger goal of this project is to account for all major plant groups which contribute to ET in this wetland. The percentage of the area covered by each plant can be estimated from remote sensing data. Crop coefficients for each species are taken from literature, or extrapolated from the data we collect. Once this data is developed it will be possible to accurately assess ET in the wetland of the San Joaquin Valley.

The comparison of wetland ET to ETo in this paper will allow us to test our conceptual understanding of the factors determining wetland ET so that these factors can be integrated with soil salinity surveys and data on plant species abundance and distribution from remote sensing to create a model of wetland ET, salinity, and plant community interactions. Such a model will be valuable in developing best practices for irrigation that will promote desirable plant species which support wildlife while maintaining high water quality and water use efficiency.

METHODS

Evaporation and transpiration, collectively ET, can be measured directly in small systems by using changes in weight to track the extent of evaporation in a closed system such as a potted plant or a pan of moist soil. Doing this on the scale of an agricultural field or a wetland is not possible. Instead, people have found ways to extrapolate estimates of total system ET from the limited direct measurements which are possible. These estimates can be compared to the direct measurements of ET in order to check their accuracy [3].

One approach to estimating ET in larger systems is the use of an energy balance equation. The underlying assumption of this method is that the sum of energy entering, stored in, and leaving the system, is zero. This follows from the principle of conservation of energy, the first law of thermodynamics. The radiant energy coming from sunlight is the major source of energy entering the system, and can be directly measured using a radiometer. This energy can go into a number of places. Some of it will raise the temperature of the air and the soil. Some energy is used by plants in photosynthesis and stored in the plant tissue, but this fraction is very small in comparison to other components of the energy balance. Heat stored in or lost from soil and air can be estimating by measuring changes in air and soil temperature and moisture.

Once the energy entering and leaving as radiation and the energy stored as sensible heat in air and soil has been accounted for, any difference must be due to the latent heat sink of evaporating water. The amount of energy needed to vaporize an amount of water at a given temperature is well known, and so the amount of water which has evaporated can be estimated. Whether the water is being directly evaporated from the soil surface, or if it is transpired through plants, the energy involved is the same.

There are a number of equations which utilize energy balance principles to estimate ET. Different equations are better suited to certain conditions, and so the equation in use is usually selected based on local conditions. The large number of variables involved in any energy balance equations, and the variety of such equations in use, make comparisons across diverse environments difficult. While measurements of ET are extremely valuable in understanding a wide range of ecosystems, comparisons of ET data must be made cautiously, only in cases where most important conditions are similar.

The State of California operates an irrigation management information system (CIMIS) which has numerous weather stations using energy balance equations to estimate potential ET (ETo). In order to provide a standard context for measurements of ETo is defined as the ET of well watered grass pasture [4]. The ETo calculated at these stations reflects the ET patterns in the surrounding area, although different plant communities and non-irrigated areas will experience different amounts of ET.

This project is operating a weather station in a wetland near Los Banos, CA. This station will gather ET data that can be compared to the standardized ETo data from nearby stations in the CIMIS network. Major differences in ET patterns a will be explained according to differences in plant community and water availability.

STUDY SITES

Gadwall Unit

A BREB station is located on a seasonal wetland at the Gadwall unit within the Los Banos Wildlife Management Area complex, and is operated and maintained by the California Department of Fish and Game (CDFG). According to correspondence with CDFG managers, the wetland unit was flooded in September 2006 and water was drawn-down in mid-March 2007. The dominant wetland vegetation is swamp timothy (*Crypsis schoenoides*) interspersed with stands of bulrush (*Scirpus martimus*), cocklebur (*Xanthium strumarium*), and other moist soil vegetation. Since the swamp timothy emerges only after the draw-down of water, there is a period of several weeks during which most of the wetland is bare soil with little vegetative cover. During March and April moist soil plants, especially swamp timothy, germinate and grow. By June soil moisture falls to a level which no longer supports most of the plants leading them to senesce.

CIMIS Stations

Three stations that report ET data to the CIMIS network were selected primarily for their geographic proximity to the Gadwall unit. The stations are located at Firebaugh/Telles (referred to hereafter as Firebaugh), Los Banos, and Merced. They are listed in the CIMIS network by number as 7, 56, and 148 respectively.

According to the Department of Water Resources website, "CIMIS is using a well-watered actively growing closely clipped grass that is completely shading the soil as a reference crop at most of it's over 120 weather stations."[5] Limited information on the specific vegetation and water management practices surrounding individual sites were obtained from the CIMIS website. The Firebaugh site is located on lawn turf with some trees and is irrigated with sprinklers, the Los Banos site is a grass pasture which is flood irrigated, and the Merced site is described as grass over pasture and is flood irrigated.

CONCEPTUAL MODEL OF SEASONAL ET

According to a Bureau of Reclamation document entitled "Review of Wetland Evapotranspiration Literature" [], the factors which primarily control ET are the amount of incoming solar radiation, the VPD (vapor pressure deficit) of the air above the surface, wind speed, and the physical characteristics of the site including plant community makeup. Since the CIMIS stations and the Gadwall unit are near to one another incoming solar radiation and most meteorological conditions, such as wind speed and precipitation, should be very similar at all times. Both sites should experience greater ET in the summer as solar radiation provides more energy to drive ET. Major differences in ET between the wetland and the CIMIS sites will likely result from the fact that CIMIS sites have a constant crop cover of live grass and are continuously irrigated throughout the year, while the wetland's irrigation and vegetation are governed by seasonal cycles.

Before and immediately following drawdown in mid-March, soils at the Gadwall unit are saturated with water, but by June they are dessicated, with less than 5% moisture by mass (unpublished data). As long as soils are completely wetted, high VPDs in the air above the soil will drive high rates of ET. During the summer, when soils in the wetland have dessicated, VPD between soil and air will be much lower. VPD at CIMIS sites should remain high, perhaps even increasing in the summer as dry air moves over the well watered pastures where the CIMIS stations are located.

Physical characteristics, such as plant community structure, will be relatively constant at the irrigated and mowed lawns of the CIMIS sites, while the plant community at the Gadwall site will vary seasonally. The literature suggests that effects of vegetation on ET will vary with a number of factors [5]. All live plants will contribute to ET through their transpiration, although this may be offset by their shading of the soil [7] and the effect of creating a boundary layer which limits gas exchange between air and soil [8]. Taller plants are thought to contribute substantially to ET because of their peripheral surface area's contribution to moisture transfer [5]. Although there is no clear consensus on the impacts of vegetation on ET, we expect to see some effect on ET as the Gadwall unit transitions from standing water to bare wet earth, then to a low cover of swamp Timothy, and finally as the swamp Timothy senesces leaving a cover of dead plant matter. The CIMIS sites should not undergo any major seasonal changes in plant community structure, and so any impacts of vegetation changes at the Gadwall site should be highlighted in contrast to the consistent vegetation at the CIMIS sites

DISCUSSION

In order to test our understanding of trends in ET in the wetland and to partially corroborate our estimates of ET we have compared data from our BREB station in the first 6 months of 2007 to data from stations in the California Irrigation Management Information System[6]. We expect to find some differences in ET between the CIMIS data and the BREB data, however, we hope that these differences can be explained by reference to conditions in the wetland which are different than those in the plots where CIMIS stations are located.

The general pattern and magnitude of ET during the first six months of 2007 are similar for our unit and the nearby CIMIS stations (Figure 1). However, the wetland in which the BREB station is located is subject different patterns of irrigation and species growth than the ETo plots at CIMIS stations. The relationship between CIMIS ETo and wetland ET can largely be accounted for in terms of these differences

The emergence and senescence of the swamp timothy *Crypsis schoenoides,* which dominates the site, occurs in a period of about 2 months following drawdown. Following drawdown in March the site is dominated by wet bare earth. During this period wetland ET exceeds ETo at the CIMIS plots. The lower ET at CIMIS sites may be attributed to the shading of ground by the plants, an affect also observed by Cooley and Idso (1980), who found that a low crop cover reduces ET versus pan evaporation in proportion to their effect on the radiative properties of the surface, and the observation of Snyder and Boyd (1987) that vegetation can reduce ET losses by reducing wind speed over the surface.

When the water level at the Gadwall unit has fallen below the soil surface,~ julain day 75, ET at the Gadwall unit falls below CIMIS ETo. One would expect E to be lower in a situation where water is held within the soil matrix. The fact that ETo is higher than wetland ET during this period, despite abundant moisture in the wetland's soil, suggests that the grass cover in the ETo plots is increasing water usage through its transpiration.

By May swamp timothy forms a consistent low ground cover over the wetland surface. At this point the conditions at the Gadwall unit most closely resemble those at a reference ET plot. There is sufficient soil moisture and the dominant species is a low ground cover. The similarities between CIMIS sites and the Gadwall site in terms of physical structure and VPD during this period agree with the observation that wetland ET and potential ET converge during May (Figure 1).

In June the lack of irrigation and precipitation leads to the senescence of this ground cover as well as decreased air-soil VPD. The dead plant material which remains on the surface may also create a "mulch effect" as reported in Kadlec et al. (1988), sheltering the soil from solar radiation and air exchange with the atmosphere while not transpiring moisture as live plants would. This would have the effect of further reducing ET. Limited data from soil moisture sensors suggest that the remaining soil moisture is extremely tightly bond to the soil matrix by this point, though soil in deeper layers may still be releasing moisture to the atmosphere through the abundant cracks in the surface.

As the season progresses both the Gadwall and CIMIS sites respond to increasing solar radiation with increasing levels of ET. ET at the Gadwall site also responds to the additional factors of changing physical structure and soil moisture. When these two factors approximate ETo conditions ET values from the Gadwall site converge with those of the CIMIS sites, and when conditions diverge early and late in the growing season, ET values diverge from ETo values as well.

CONCLUSIONS

It is clear that ETo data from the CIMIS network alone does not provide an entirely accurate description of ET patterns in the wetland throughout the growing season. There is a definite need to account for the impact of changing vegetation patterns and moisture availability on ET. Modeling of ET based on ETo in agricultural systems is often modeled by identifying the contributions of each plant species to ET and weighing those contributions based on the percent cover and density of respective species distributions [3]. Unfortunately this approach is currently limited by the lack of timely data on species conditions and distributions.

Since the species distributions and water availability in the seasonal wetland will change throughout the growing season a set of dynamic terms or coefficients must be included in the equation, either based on a model of conditions at different times during the growing season or on real time data. Contributions of bare soil and standing water must also be incorporated into total landscape water use. These contributions could likely be assessed in the same manner as the contributions of different plants. Since all of these factors change throughout the year current data specific to species cover and soil moisture in the wetland would be required in order to model wetland ET using ETo estimates from CIMIS during any particular period.

Ongoing work with remote sensing data may allow for accurate estimation of percentage cover of each plant species at each stage of the growing season. Using the ET estimates from the BREB station in conjunction with accurate remote sensing data on species density and distribution throughout the growing season, it would be possible to develop a species coefficient (K_S) specific to each species, for open water, and bare soil. Using these species coefficients along with species density and distribution data, this model could be applied to arrive at landscape coefficients (K_L) in other similar wetlands based on ETo reported by the CIMIS network.

The effect of water availability on ET is another phenomenon which must be incorporated into a model of wetland ET. Since the species and Landscape Coefficient Method is designed for intensively managed landscapes it assumes that water inputs will be matched to the potential water needs of the plants. Thus there is no means to model the effect of decreasing soil moisture on ET from plants or bare earth.

Decreased soil moisture is a major factor in explaining differences between wetland ET and ETo in our study. Since potential ET (ETo) is measured on a well watered plot, a great deal of the incoming energy drives evaporation. In a system which does not have abundant water ET will fall below ETo estimates based on well watered plots. It may be possible to incorporate additional coefficients or terms into a model to represent the effect of the differences in water availability between the wetland and the ETo plot. Due to technical issues with our soil moisture probe and the lack of soil moisture reporting on the CIMIS network it is not possible to propose such a relationship at this time. Furthermore, any attempt to model soil moisture should regard the profile of soil moisture as one moves down from the surface. Because of cracking in the soils air may be readily exchanging moisture with soils several inches below the surface which will contain more moisture than upper soil layers. Some plants will also access this deep soil moisture with more extensive root systems. The need for data on soil moisture threatens to add an unwanted degree of complexity to the modeling of wetland ET based on CIMIS ETo data.

The ability to accurately model ET is essential for management of limited water resources. Irrigation scheduling can be optimized so that the water needs of desired plants are met with minimal impact on the water quality in the irrigation system. The development of an accurate model which estimates wetland ET using ETo data will require an understanding of important differences between wetland systems and ETo plots. Both soil moisture and plant abundance data must be incorporated either from real time remote sensing and soil moisture assessments or by developing additional models which describe changes in these variables as a function of irrigation schedules. Remote sensing, in conjunction with ongoing analysis using e-Cognition software (Quinn- personal communication, Burns et al., 2007) offers an efficient solution to the problem mapping of species densities and distributions.

The Landscape Coefficient Method may be well suited to modeling ET in situations where species densities are well known and promises to be compatible with data gathered through remote sensing. Unfortunately, since this model relies on the assumption that water inputs will keep up with potential water usage, as in the landscaping contexts for which it was developed, it is not clear that it will be compatible with the dynamic patterns of water availability in a seasonal wetland. The issue of accounting for water availability will need to be addressed before a model can be developed which will accurately describe the relationship between wetland ET and the ETo estimates of nearby CIMIS stations.

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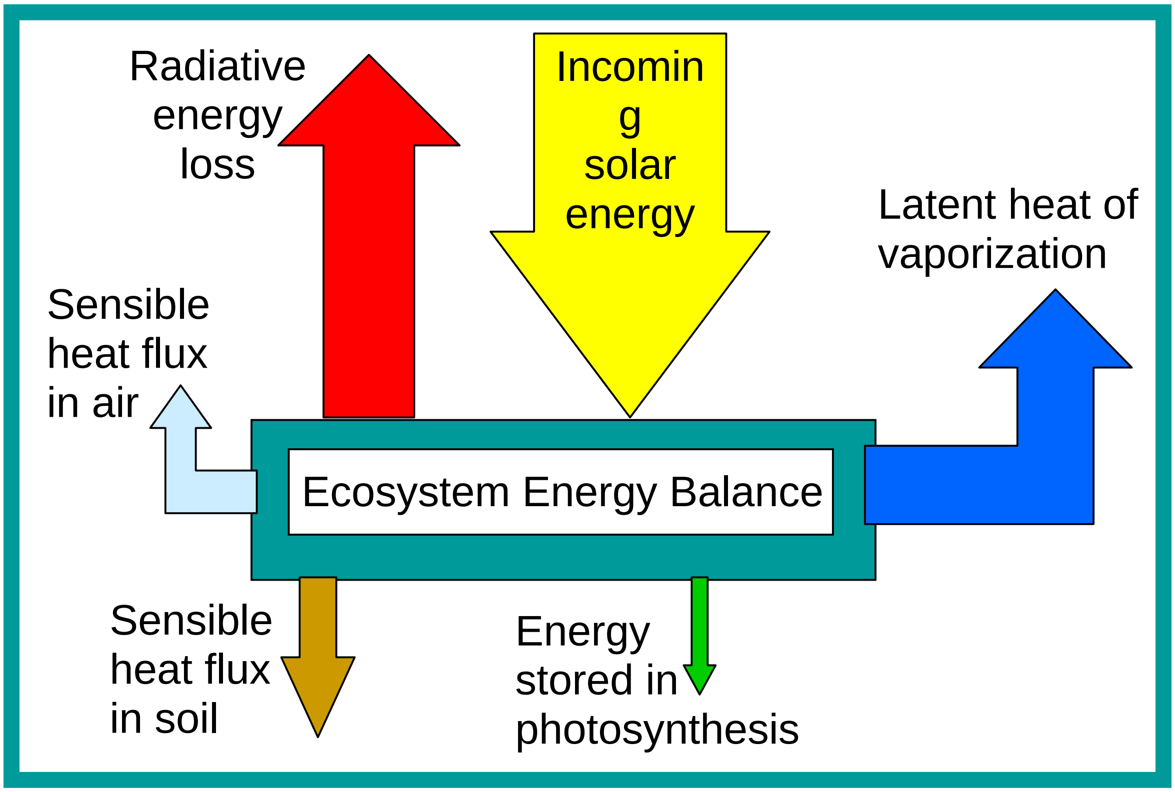

Figure 1. Model of inputs and outputs accounted for in an energy balance equation.

Figure 2. Location of BREB station – shown in early spring when water is impounded.

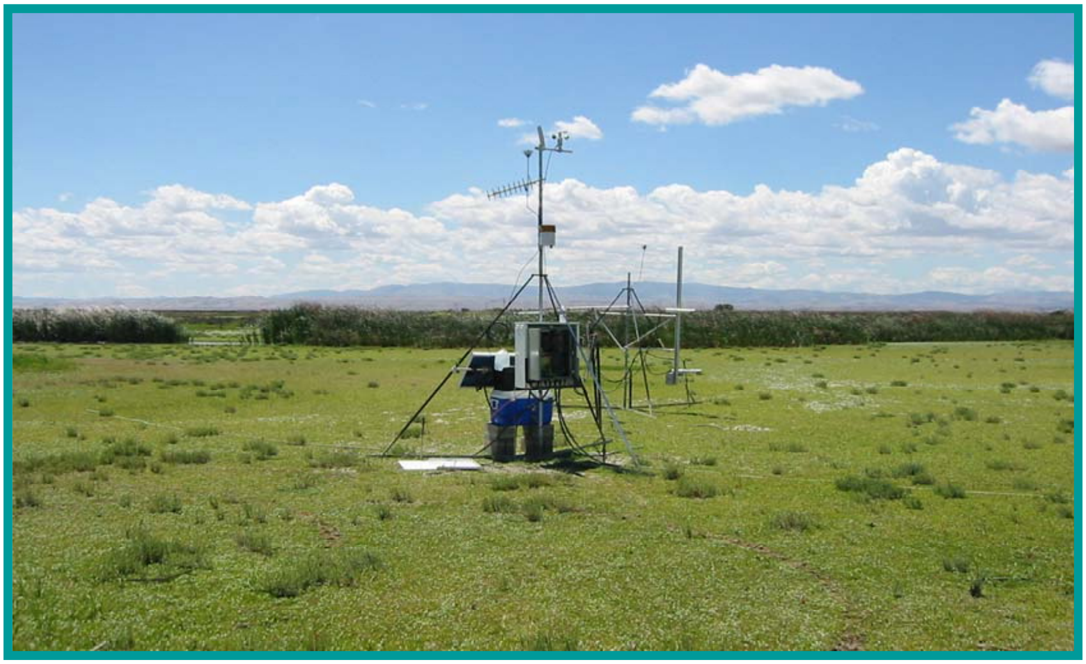

Figure 3. Bowen Ratio Energy Balance station in the Gadwall Unit of the Los Banos Wildlife Management Area. Station is located in a swamp timothy dominated field with sufficient "fetch" in the direction of the prevailing wind.

Figure 4. Study site in early July when soils have dried and most plants have senesced.

Figure 5. The CIMIS station near Los Banos. A typical CIMIS plot, which is well watered mowed grass.

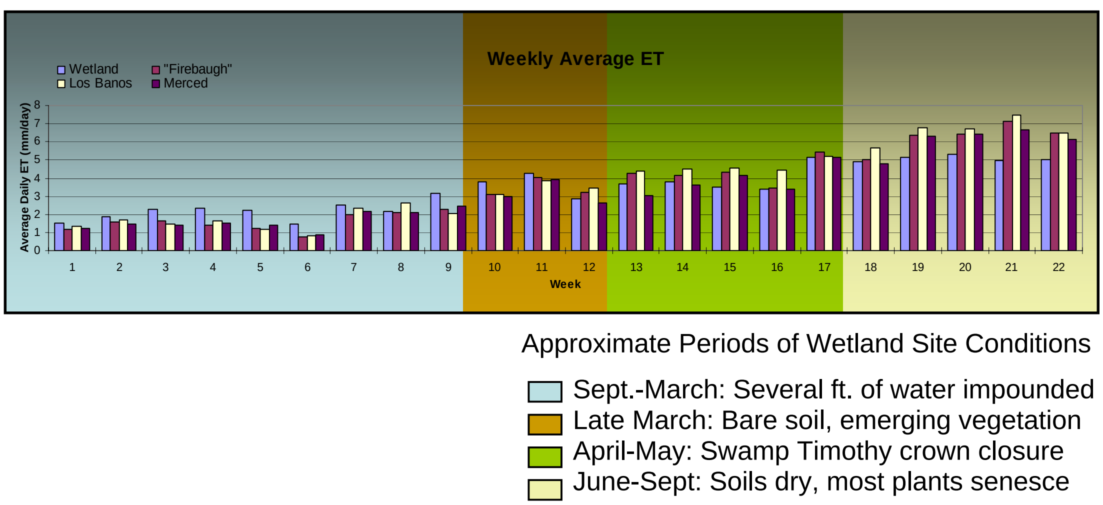

Figure 6. Graph showing weekly averages, beginning January 1st, of daily ET estimates from the wetland where our BREBS station was deployed and ETo estimates from three nearby CIMIS stations.